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UTILIZATION OF WIND POWER

J. W. van Heys

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16. Abstract

The possible power of the wind in a wind turbine is determined. From available wind measurements the "wind frequency line" is plotted, it, like the "constant water amount line," providing the basis for design of a wind turbine. Favorable results are not obtained if work is continued on the previous principle of mill construction. There are only two ways of achieving adequate power: enlarging the circumference described by the vane and utilizing higher wind velocities. The latter are present at an altitude of about 200 meters above the ground. Satisfactory performance is attained with a vane length of 60 meters. Thus it is recommended that tests running at least one year be instituted with these dimensions.

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UTILIZATION OF WIND POWER

J. W. van Heys

Summary. *Whoever concerns himself with wind power must familiarize himself with the wind velocities that occur and with the particular properties of the wind. The wind velocity increases with distance from the ground in accordance with a definite law and the gusts become flatter. It follows that it is necessary to go upward and select a wind turbine of unprecedented diameter in order to achieve high performance.* /787*

For centuries windmills and the sails of ships have converted the energy of the wind for us. Both are vanishing from the scene, since they no longer meet the needs of the times. And yet it would appear to be one of the primary tasks of the nation to learn how to harness this enormous quantity of energy, in order that it, along with the other source of energy provided gratis by nature, water power, might evermore be used to increasingly assign coal its proper value as a raw material and rescue it from destruction by burning. Many plans have already been made to place the power of the wind in the service of man, even in nontechnical circles, but when subjected to careful examination by experts it has been found time and again that execution of the plans has been uneconomical or unfeasible.

Potential Energy of the Wind

The energy of the wind, air in motion, depends on its velocity and accordingly on the pressure applied to a body. The latter in turn depends on the weight of the air, which is determined by the temperature.

At	0°	5°	10°	15°	20°	25°	30°	40° C
air density is	1.2922,	1.2657,	1.2389,	1.2115,	1.1834,	1.1537,	1.1222,	1.0514,
	50°	60°	70°	80° C				
	0.965,	0.8566,	0.7168,	0.5557 kg/m^3.				

The pressure of air against a body is

$$P = \rho v^2 f.$$

*Numbers in the margin indicate pagination in the foreign text.

If the area of pressure f = 1, and the mean mass or density of air $\rho = \frac{\gamma}{g} = \frac{1}{8}$, $P = 1/8\ v^2$ is obtained as the wind pressure[1]. From $P = 1/8\ v^2$ we obtain $A = 1/16\ v^2$ for 1 m^3 of air as the work of the wind.

The most favorable utilization of wind power in the current state of the art is achieved by means of air vanes with windmills, wind motors, and wind turbines. The maximum output that can be reached by a wind wheel is

$$L_{max} = 0.000\ 285\ v^3\ D^2, \text{ in kW.}$$

The power increases with the square of the diameter of the circle described by the vane, D. and the cube of the wind velocity. To attain significant output it is necessary to utilize high wind velocities and to select the largest possible vane circle diameter.

Wind Velocity

Wind measurements for both velocity and direction have been taken for decades at different altitudes above the ground at many stations in Germany which have recently been placed under the Reichsamt fuer den Wetterdienst [National Weather Service], where the results are further analyzed. The instruments employed for the measurements have been constantly improved, especially in recent times. The following have thus far been established as the highest wind velocities[2]:

On the German coast up to	60 m/sec
at Berlin-Tegel	30 m/sec
Sonnenblick weather station	60 m/sec
Trieste	75 m/sec
North America	80 m/sec
Japan	85 m/sec

These wind velocities and the pressures calculated from them must be taken into account in calculation of the strength of structures.

Gusts

Wind velocities are never uniform. Rather they occur in individual squalls

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[1] In Bauingenieur, Vol 7, 1922, p. 491, Buschegger states that the wind pressure can be no higher than $0.1\ v^2$.

[2] Bauingenieur, Vol 9, 1924, Nos. 13 and 14.

of varying duration, particularly in the vicinity of the ground. The higher the wind velocities, the stronger are the squalls, which we term gusts. Even at low wind velocities the velocity undergoes constant change. Figure 1 illustrates low, medium and high wind velocities registered with the gust recorder at 41 meters above the ground on Telegraphenberg [Telegraph Hill] at Potsdam. It is to be seen that velocities of 0-10 m/sec are to be anticipated with medium velocities, which range around 5-6 m/sec over a period of an hour. Gusts occur with a frequency of 30-40 an hour, i. e., they are of an average duration of 2/3-2 minutes. In the case of higher wind velocities, which on the hourly average may exceed 10 m/sec, to reach 10.8 m/sec and 10.9 m/sec, 50-60 gusts occur per hour. The velocities range from 2-22 m/sec. In 1937 the mean wind velocity exceeded 11 m/sec at the measurement altitude of 41 meters above the ground for only 58 hours. On one day it reached the daily average of 11.10 m/sec and on two days daily averages of 10.14 and 10.22 m/sec, otherwise always remaining below 10 m/sec. The highest mean wind velocity reached in any hour amounted to 15.8 m/sec. To gain an idea of wind frequencies during the year it is necessary to tabulate the mean hourly velocities arranged in order of magnitude. It has been found as the mean of 25 years of observation /788
that:

winds of a velocity of 0-2 m/sec occur 27 hours during the year,
winds of a velocity of 2-2.9 m/sec occur 831 hours during the year,
winds of a velocity of 3-3.9 m/sec occur 1350 hours during the year,
winds of a velocity of 4-4.9 m/sec occur 1661 hours during the year,
winds of a velocity of 5-5.9 m/sec occur 1722 hours during the year,
winds of a velocity of 6-6.9 m/sec occur 1287 hours during the year,
winds of a velocity of 7-7.9 m/sec occur 868 hours during the year,
winds of a velocity of 8-12 m/sec occur 720 hours during the year,
winds of a velocity over 12 m/sec occur 50 hours during the year.

Figure 2 shows the "wind frequency curve" plotted from these figures. The mean annual velocity of 5.22 m is entered, while the heavy lines at 3.5 m and 815 m show the limits of previous wind utilization by means of windmills.

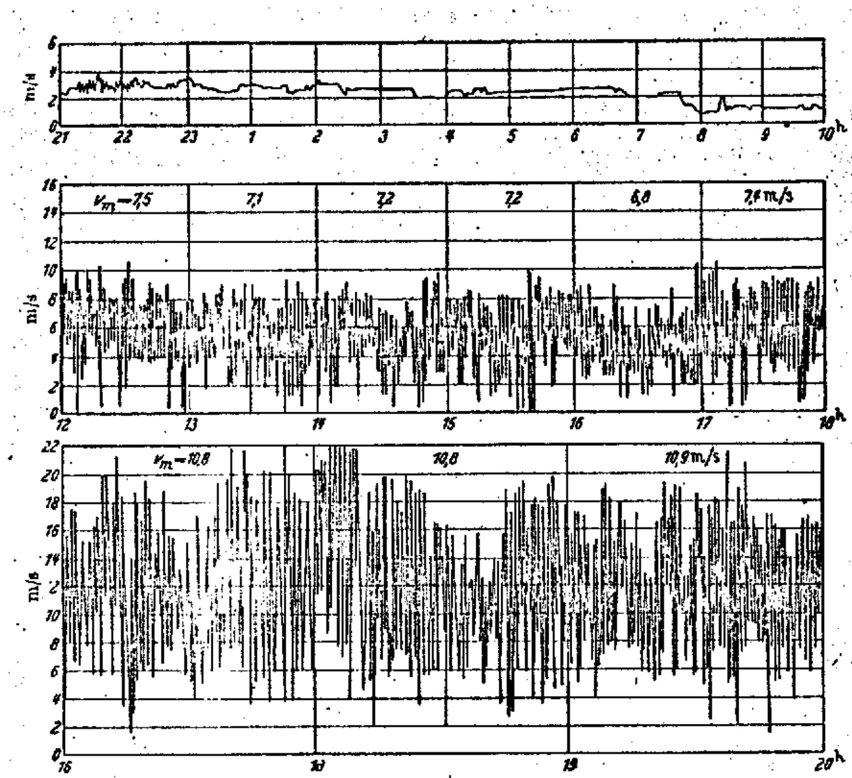

Figure 1. Minimum, Mean, and Maximum Wind Velocities in 1937.

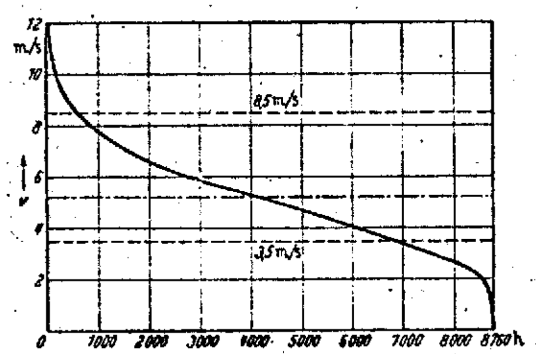

Figure 2. Wind Frequency Curve.

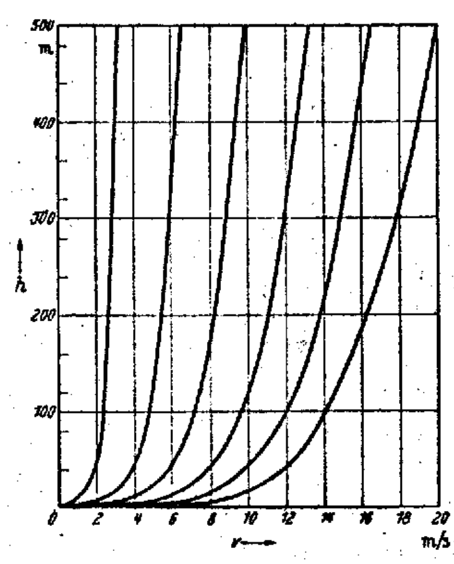

Figure 3. Increase in Wind Velocity with Altitude According to Hellmann.

Increase in Wind Velocity with Altitude

Wind measurements at higher altitudes above the ground have shown that wind velocity generally increases with altitude above the ground. From a series of such measurements Hellmann derives the relation

$$\frac{v}{v} = \sqrt{\frac{h}{h_0}},$$

which is assumed to be valid starting at 16 meters above the ground (v_0 = wind velocity at measurement altitude h_0). This equation is not to be regarded as an unequivocally established fact but as a rough approximation to actual conditions, if one is to gain an idea of the winds prevailing at higher altitudes. More recent observations and measurements are reported to have revealed a sharper increase in wind velocity with the altitude than is obtained by calculation with Hellmann's equation. Since the new observations and measurements have not yet been completed, only those on the basis of which definitive laws may be formulated, primarily Hellmann's equation will be employed here. It will be easy subsequently to arrive at correct conclusions from more recent results and adopt them as the basis for further treatment.

Roughly, the velocities shown in Figure 3 are obtained by calculation at altitudes of 60-500 m for winds which might be utilized. These velocities are derived from the mean hourly velocities of 2-12 meters measured at 41 meters above the ground at Potsdam.

Uniformity of the Wind

There is one last property of wind which is to be taken into consideration for the purpose of its utilization; this is the decrease in the relative strength of gusts with altitude which has been established by observation. The higher one goes, the weaker gusts apparently are in relation to the prevailing winds. The intensity of gusts probably still increases with altitude further up as well, but not to the same extent as the increase in wind velocity, so that gusts are not so strongly felt as in vicinity of the ground. Gusts disappear only at altitudes of several thousand meters, which are not considered for purposes of wind utilization.

A curve has also been plotted on the basis of detailed measurements for the decrease in gusts with altitude. This curve is illustrated in Figure 4. The studies of this question have not yet been completed, so that the curve shown may be regarded only as a tentative pattern.

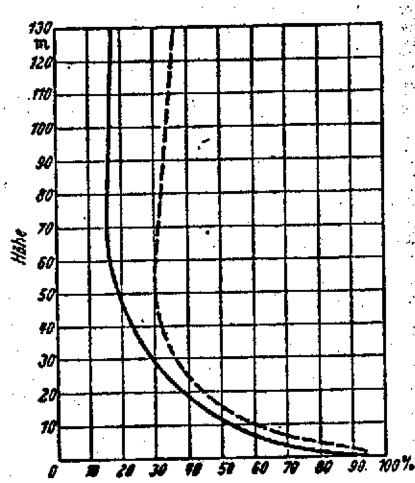

Figure 4. Decrease in Wind Velocity Fluctuations with Altitude According to Bongards.

Utilization of Wind Power

Windmills, which up to the present have been the only devices employed (except for wind motors) to derive work from the wind, generally have a vane describing a circle of 22 meters. Only one windmill in Germany has one describing a circle of 30 meters. Only at a wind velocity of 3.5 m/sec do they begin to yield work, and they are disengaged at 8.5 m/sec, since the pressure of the wind presents a danger to the vane.

If the most favorable vane configuration according to La Cour is adopted, one in which the width is 1/4 to 1/5 of the vane length, and the reinforced length is about 3/4 of the vane length, an ideal windmill performance at wind velocity

	v = 4	6	8	10 m/sec	
of	L = 8.83	29.8	70.6	131 kW	is obtained.

These are performances of no importance whatever to the power economy. The mill is too expensive for the individual consumer of current, it is not always ready for operation, and the consumer can scarcely make use of the power stored. Hence preference is always given to connection to the regional grid or to the internal combustion engine, which may be placed in operation at any time and from any location. Even for the farmer living away from the stream of traffic the construction of a windmill with a storage battery as a dispenser of light and power can be given consideration only in the rarest cases. The total costs of installation and maintenance cannot be reconciled with the advantages that such a plant might yield.

If the diameter of the circle described by the vane is increased to 60 meters, the performance is increased by the square of the factor of the increase in diameter. (The factor is 60/22 = 2/73, and the square of the latter $2/73^2 = 7.45$.) The performances are:

at wind velocity	v =	4	6	8	10 m/sec
	L =	65.7	221.6	525.3	1026 kW.

Nor are these performances in any way satisfactory. It follows that there are /789
only two methods left by which one can achieve adequate performances:

1; increase in the diameter of the circle described by the vane, and

2; utilization of higher wind velocities.

Increase in the diameter of the circle described by the vane is basically a matter of material. Wind vanes of a length greater than 20 meters cannot be made of wood. Heavy metals have the advantage that the great weights, because of their inertia, are better able to compensate to some extent for the wind gusts. However, great weights complicate the overall design. Light metals in turn yield other advantages, but are expensive. A study must be made in each individual case to determine where the operating and economic advantage lies.

According to tests and calculations which have been performed it appears to be possible to manufacture self-supporting wind vanes of a length of up to 60 meters. If the form regarded by La Cour as the most advantageous for derivation of the greatest possible energy is imparted to them, the width would be about 12 meters and the reinforced length about 45 meters. It is sufficient for current calculations to regard the wind as striking at a distance of approximately 37.5 meters from the hub. As stated previously, a wind velocity of 30 meters is to be adopted as the basis for calculation of the strength. Thus the wind pressure on a vane amounts to

$$P = 12 \cdot 45 \cdot 0.125 \cdot 302 = 60{,}750 \text{ kg.}$$

Striking at a distance of 37.5 meters from the hub, the wind generates a bending moment of 2,278,125 kgm, this requiring a moment of resistance of $W = 45{,}753$ cm^3 with a bending strength of 5000 kg/cm^2 for its absorption.

An annular cross-section with a diameter of 2 meters and a wall strength of 2 centimeters has a moment of resistance of 62,105 cm^3. This is enough to absorb the loads. Thus it is found that the dimensions for vane design can be kept within quite moderate limits.

Windmill vanes with a streamlined outer skin have shown that with vane circle diameters of normal magnitude (16 to 22 meters) almost the same performance is achieved with 2 to 3 vanes as with 4 vanes. Thus with vanes up to 30 meters in length (a vane circle diameter of 60 meters), about 4 vanes might be considered standard for design, and 4 to 6 vanes with a vane length of 60 meters, if

$$\frac{u \text{ (circumferential velocity)}}{v \text{ (wind velocity)}} = 6$$

is to be achieved.

If the vane is tapered outward and the reinforcement is kept as light as possible, it is possible to keep the weight of a vane to 40 tons. This great weight may be of decisive importance in construction of the entire wind power machine for choice of the number of vanes. An effort is to be made to keep the number of vanes as small as possible, so long as impairment of the energy derivation is avoided.

The other method of obtaining higher performances consists in utilization of higher wind velocities. Such velocities are available at a high altitude above the ground (Figure 3). Thus by means of the Hellmann curves referred to previously one can determine roughly the wind velocities to be expected at altitudes of 100, 200, 300, 400, and 500 meters above the ground. By means of Figures 2 and 3 one can also plot the wind frequency curves for the various altitudes. They can provide an idea of the wind velocities to be expected at the various altitudes. These curves are shown in Figure 5. Whether they are to be regarded as decisive, and to what extent, depends on the extent to which Hellmann's formula is correct. More recent observations suggest that the number of hours of the higher wind velocities is greater than indicated by the lines in Figure 5.

We know from hydraulic engineering that we can expect utilization of the amount of water in a stream on 90 to 120 days to be economical. If turbines /790
and generators are designed for performances present on fewer days, the economic

effectiveness of the plant decreases. It is to be noted that large machines operate with unsatisfactory efficiency when the delivery of water is small. Although the conditions obtaining in the case of water turbines cannot be applied directly to wind turbines, these conditions may nevertheless be regarded as guidelines, the more so as empirical data on wind turbines are lacking. The limit of economical construction again depends on different factors for wind turbines than for water turbines. We will follow as authoritative the method indicated here to determine how far one should and can go. We will assume that no particular difficulties are involved in utilizing wind velocities of 15 to 16 m/sec, which on the wind scale of the German Naval Observatory as heavy, gale-force winds. According to the Hellmann curves (Figure 5), this wind force occurs so rarely at the altitudes suitable for utilization in turbines (200 to 300 meters above the ground) that utilization appears to be scarcely feasible. According to recent observations, winds of 12 m/sec at about 250 meters above the ground occur during 1600 hours. Should this be correct, it is worthwhile to construct an approximate picture of the wind on the basis of these observations. Figure 6 shows how such a wind frequency curve might look. The question of whether it is entirely accurate must be deferred for the time being. It has been plotted on the basis of previous measurements and observations. The following performances have been calculated from them for a wind turbine with a vane length of 60 meters or a vane circle diameter of 130 meters (hub 10 meters in diameter):

at v =	4	6	8	10	12	14	16 m/sec
L =	308	1034	2466	4816	8323	13,216	19,726 kW.

The utilization period will amount ot about 1500 hour at a mean wind velocity of 8.7 m/sec on the annual average. At an average efficiency of about 70%, $30 \cdot 10^6$ kwh can be obtained annually.

Experiments must be conducted to determine the extent to which the actual design deviates from the theoretical. Such experiments are absolutely indispensable in the interests of the national economy.

In practical execution of the experiment care should be taken to make certain that the higher wind velocities of the wind turbine do not become dangerous. This can come about if the vanes are set in another position relative to the wind when a certain wind velocity is exceeded, as occurs with the Kaplan turbine[3], or if particular equivalent drag surfaces are made to stand out on the surface of the vane, as Bilau did with his trailing vanes.

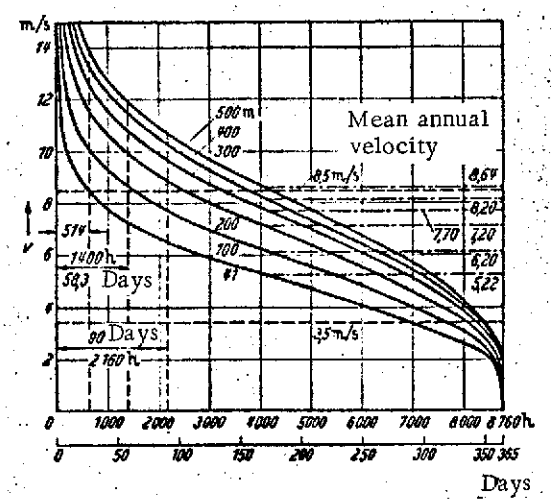

Figure 5. Wind Frequency Curves at Various Altitudes.

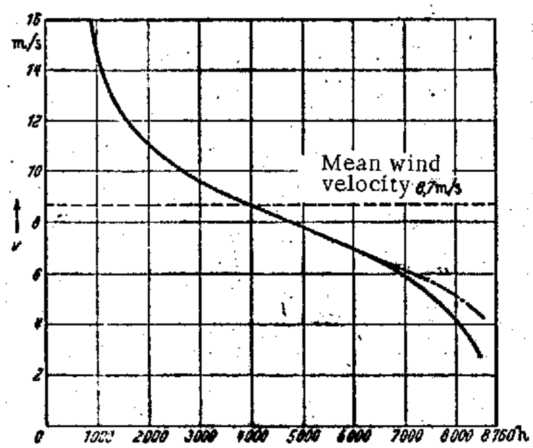

Figure 6. **Probable Wind Frequency Curve at Altitude of about 250 m.**

It appears to be necessary first of all to conduct measurements for a period of at least one year with suitable instruments in order to determine

1, wind velocities and wind directions,

2, the work yielded by the vane wave in the course of a year.

The measurement devices must provide a graphic representation of the power of the wind present at all times. Only after such an experiment has been conducted can an idea be gained of the operating expenses and the economic efficiency of the plant.

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[3]See, for example, ETZ, Vol. 57, 1936, p. 702, Figure 6.